HL-LHC Accelerator Status & Schedule

Oliver Brüning
For the HL-LHC Project team
The LHC is NOT a Standalone Machine:

- **SPS**: 26 -> 450 GeV
- **PS**: 1.4 -> 26 GeV
- **PSB**: 50 MeV -> 1.4 GeV
- **LINAC2**: 50 MeV
- **LHC**: 450 -> 7000 GeV
- **PS**: 1.4 -> 26 GeV
The LHC is NOT a Standalone Machine:

SPS: 26 -> 450 GeV

PS: 1.4 -> 26 GeV

PSB: 50 MeV -> 1.4 GeV

LINAC2: 50 MeV

LHC: 450 -> 7000 GeV

Dedicated project for the LHC Injector complex Upgrade (LIU)
Performance Projections up to HL-LHC:

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Run I
Run II
Run III

0.75 \(10^{34}\) cm\(^{-2}\)s\(^{-1}\)
50 ns bunch
high pile up \(\sim 40\)
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Performance Projections up to HL-LHC:

- **Run I**
  - 0.75 $10^{34}$ cm$^{-2}$s$^{-1}$
  - 50 ns bunch
  - high pile up $\sim$40

- **Run II**
  - 1.5 $10^{34}$ cm$^{-2}$s$^{-1}$
  - 25 ns bunch
  - high pile up $\sim$40

- **Run III**

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Performance Projections up to HL-LHC:

Run I
- \(0.75 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 50 ns bunch
- high pile up \(\sim 40\)

Run II
- \(1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- high pile up \(\sim 40\)

Run III
- \(1.5 - 2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- 25 ns bunch
- very high pile up \(> 60\)
Performance Projections up to HL-LHC:

- Cryogenic limit &
- Radiation Damage of triplet magnets

Run I
0.75 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
50 ns bunch
high pile up \(\sim 40\)

Run II
1.5 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
25 ns bunch
high pile up \(\sim 40\)

Run III
1.5 -2.2 \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
25 ns bunch
very high pile up > 60

Technical limits (machine and experiments) like e-cloud UFOs!
Goal of High Luminosity LHC (HL-LHC):

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

Prepare machine for operation beyond 2025 and up to 2035

Devise beam parameters and operation scenarios for:

# enabling at total integrated luminosity of 3000 fb\(^{-1}\)

# implying an integrated luminosity of 250 fb\(^{-1}\) per year,

# design oper. for \(\mu \leq 140\) (\(\Rightarrow\) peak luminosity of 5 \(10^{34}\) cm\(^{-2}\) s\(^{-1}\))

> Ten times the luminosity reach of first 10 years of LHC operation!!
LHC Limitations and HL-LHC Challenges:

- Technical bottle necks (e.g. cryogenics) ➔ New addit. Equipment
- Insertion magnet lifetime and aperture:
  ➔ New insertion magnets and low-β with increased aperture
- X-ing angle Geometric Reduction Factor: ➔ SC Crab Cavities
  ➔ New technology and a first for a hadron storage ring!
- Performance Optimization: Pileup density ➔ luminosity levelling
  ➔ devise parameters for virtual luminosity >> target luminosity
- Beam power & losses ➔ additional collimators in cold region
- Machine efficiency and availability:
  # R2E ➔ removal of all electronics from tunnel region
  # e-cloud ➔ beam scrubbing (conditioning of surface)
  # UFOs ➔ beam scrubbing (conditioning of surface)
Eliminating Technical Bottlenecks

Cryogenics P4 - P1 - P5

8 x 18 kW @ 4.5 K
1'800 SC magnets
24 km and 20 kW @ 1.9 K
36'000 tons @ 1.9 K
96 tons of He

Cryogenic plant
Eliminating Technical Bottlenecks
Cryogenics P4- P1 –P5

New Plant ≥ 6 kW in P4 (LS2)
New 18 kW Plants in P1 and P5 (LS3)

8 x 18 kW @ 4.5 K
1'800 SC magnets
24 km and 20 kW @ 1.9 K
36'000 tons @ 1.9 K
96 tons of He
HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb⁻¹

- Q2: 27 MGy
- Cold bore insulation: ≈ 35 MGy
- MCBX3: 20 MGy

7+7 TeV proton interactions
IT quadrupoles
MCBX-1
MCBX-2
MQSX
MCTX nested in MCBX-3
MCSEX

peak dose longitudinal profile

Distance from IP [m]

Peak dose [MGy / 300 fb⁻¹]
HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb$^{-1}$

Need to replace existing triplet magnets with radiation hard system (shielding!) such that the new magnet coils receive a similar radiation dose @ 10 times higher integrated luminosity!!!!!!
HL-LHC Challenges: Crossing Angle I

Insertion Layout:

Parasitic bunch encounters:
Operation with ca. 2800 bunches @ 25ns spacing ➔ approximately 30 unwanted collision per Interaction Region (IR).

➔ Operation requires crossing angle

non-linear fields from long-range beam-beam interaction:
efficient operation requires large beam separation at unwanted collision points

➔ Separation of 10 - 12 σ ➔ large triplet apertures for HL-LHC upgrade!!
HL-LHC Upgrade Ingredients: Triplet Magnets
HL-LHC Upgrade Ingredients: Triplet Magnets

- Nominal LHC triplet: 210 T/m, 70 mm coil aperture
  - ca. 8 T @ coil
  - 1.8 K cooling with superfluid He (thermal conductivity)
  - current density of 2.75 kA / mm²
- At the limit of NbTi technology (HERA & Tevatron ca. 5 T @ 2kA/mm²)!!!
HL-LHC Magnets:

- LHC triplet:
  - 210 T/m, 70 mm bore aperture
  - $\Rightarrow$ 8 T @ coil (limit of NbTi tech.)
HL-LHC Magnets:

- LHC triplet:
  210 T/m, 70 mm bore aperture
  \( \Rightarrow 8 \, \text{T} @ \text{coil} \) (limit of NbTi tech.)

- HL-LHC triplet:
  140 T/m, 150 mm coil aperture
  (shielding, \( \beta^* \) and crossing angle)
  \( \Rightarrow \text{ca. 12 T} @ \text{coil} \) \( \Rightarrow 30\% \) longer
HL-LHC Magnets:

- **LHC triplet:**
  210 T/m, 70 mm bore aperture
  → 8 T @ coil (limit of NbTi tech.)

- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  (shielding, $\beta^*$ and crossing angle)
  → ca. 12 T @ coil → 30% longer
HL-LHC Magnets:

- LHC triplet:
  210 T/m, 70 mm bore aperture
  → 8 T @ coil (limit of NbTi tech.)
- **HL-LHC triplet:**
  140 T/m, 150 mm coil aperture
  (shielding, $\beta^*$ and crossing angle)
  → ca. 12 T @ coil → 30% longer
  - Requires Nb$_3$Sn technology
    → brittle material type (fragile)
    → ca. 25 year development for this new magnet technology!
- US-LARP – CERN collaboration
New Interaction Region lay out

Longer Quads; Shorter D1 (thanks to SC)

Thick boxes are magnetic lengths -- Thin boxes are cryostats
LHC Challenges: Crossing Angle II

geometric luminosity reduction factor:

large crossing angle:

- reduction of long range beam-beam interactions
- reduction of beam-beam tune spread and resonances
- reduction of the mechanical aperture
- increase of effective beam cross section at IP
- reduction of luminous region
  - reduction of instantaneous luminosity
  - inefficient use of beam current!
HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

\[ F = \frac{1}{\sqrt{1 + \Theta^2}}, \quad \Theta = \frac{\theta_c \sigma_z}{2 \sigma_x} \]

\[ F(\beta^*) \]

- effective cross section

IPAC 2015, Mai 2015, Richmond, USA
HL-LHC Upgrade Ingredients: Crab Cavities

Geometric Luminosity Reduction Factor:

\[ F = \frac{1}{\sqrt{1 + \Theta^2}}; \quad \Theta \equiv \frac{\theta_c \sigma_z}{2\sigma_x} \]

\[ F(\beta^*) \]

Effective cross section

HL-LHC LHC
Crab Cavities:

- Reduces the effect of geometrical reduction factor
- Independent for each IP
- Noise from cavities to beam?!?
- Impedance and HOM?
- Challenging space constraints:
  - requires novel compact cavity design

\[
F = \frac{1}{\sqrt{1 + \Theta^2}}, \quad \Theta = \frac{\theta_c \sigma_z}{2 \sigma_x}
\]
Latest cavity designs toward accelerator

3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

Double ¼-wave: Coaxial couplers with hook-type antenna

4-rod: Coaxial couplers with different antenna types
Latest cavity designs toward accelerator

3 Advanced Design Studies with Different Coupler concepts

RF Dipole: Waveguide or waveguide-coax couplers

Double ¼-wave:

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

Review in 2013
Latest cavity designs toward accelerator

3 Advanced Design Studies with Different Coupler concepts

Review in 2013

Double $\frac{1}{4}$-wave:

Concentrate on two designs in order to be ready for test installation in SPS in 2016/2017 TS

Present baseline: 4 cavity/cryomod TEST in SPS under preparation for 2017

RF Dipole: Waveguide or waveguide-coax couplers
And excellent first results: RF Dipole

Recent results from Measurements @ CERN

Initial goal was 3.5 MV however $\Delta V > 5$-6 MV would ease integration
And excellent first results: DQW

Recent results from Measurements @ CERN

CERN SM18 Cold test @2K
Cavity: Crab_DQW

DQWR prototype (17-Jan-2013) [BNL]
HL-LHC Challenge: Event Pileup Density

Vertex Reconstruction for $0.7 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1} @ 50\text{ns}$

$Z \rightarrow \mu\mu$ event from 2012 data with 25 reconstructed vertices
HL-LHC Challenge: Event Pileup Density

Vertex Reconstruction

Extrapolating to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ implies:

$\mu = 280; \mu_{\text{peak}} > 500$ @ 50ns bunch spacing

$\mu = 140; \mu_{\text{peak}} = 280$ @ 25ns bunch spacing
Vertex Reconstruction

HL-LHC Performance Optimization:
Use leveling techniques for keeping average Pileup around $140$ events per bunch crossing.

$\rightarrow$ level luminosity at $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

$\rightarrow <\mu> = 140; \mu_{\text{peak}} = 280$ @ 25ns bunch spacing.
LHC Challenges: Beam Power

Unprecedented beam power:

- potential equipment damage in case of failures during operation
- In case of failure the beam must never reach sensitive equipment!
LHC Challenges: Beam Power

Unprecedented beam power:

- potential equipment damage in case of failures during operation

- In case of failure the beam must never reach sensitive equipment!

Stored Beam power: HL-LHC > 500 MJ / beam
LHC Challenges: Beam Power

Unprecedented beam power:

Worry about beam losses:

Failure Scenarios ➔ Local beam Impact

⇒ Equipment damage
⇒ Machine Protection

Lifetime & Loss Spikes ➔ Distributed losses

⇒ Magnet Quench
⇒ R2E and SEU
⇒ Machine efficiency
LHC Challenges: Quench Protection

Magnet Quench:

➔ beam abort ➔ several hours of recovery

HL LHC beam intensity: \[ I > 1 \text{ A} \Rightarrow > 7 \times 10^{14} \text{ p /beam} \]

Quench level: \[ N_{\text{lost}} < 7 \times 10^8 \text{ m}^{-1} \Rightarrow < 10^{-6} N_{\text{beam}}! \]

(compared to 20% to 30% in other superconducting rings)

➔ requires collimation during all operation stages!

➔ requires good optic and orbit control!

➔ HL-LHC luminosity implies higher leakage from IP & requires additional collimators

➔ Which we have demonstrated during RunI
DS collimators – 11 T Dipole (LS2 -2018)
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DS collimators – 11 T Dipole (LS2 -2018)
Prototyping of the by-pass crystostat (QTC) for the installation of a warm collimator in the cold dispersion suppressors.

Magnet: prototypes reached 11 T field in March 2013!
Nominal LHC Operation Cycle:

- Beam dump
- Ramp down/precycle
- Injection
- Ramp
- Squeeze
- Collide
- Stable beams

Nominal LHC Operation Cycle:

- Ramp down: 35 mins
- Injection: ~30 mins
- Ramp: 12 mins
- Squeeze: 15 mins
- Collide: 5 mins
- Stable beams: 0 – 30 hours

Operational Turn around time of 2 - 3 hours ➔ Efficiency = time in physics / scheduled time

M. Lamont @ Evian LHC Operation workshop

Efficiency = time in physics / scheduled time
Operation experience in 2011 and 2012:

- Only ~30% of the fills are dumped by operation.

- corresponds to ca. 40% machine efficiency (time actually spend in physics divided by scheduled time for physics operation)

- 3000 fb-1 for HL-LHC will require significantly better machine efficiency!!! and average fill length above 6 hours (ca. 10 hours)!

J. Wenninger @ Evian LHC Operation workshop
HL-LHC Challenge: Machine Efficiency

Integrated Luminosity

- Operation experience in 2011 and 2012:
  - Only ~30% of the fills are dumped by operation.

- corresponds to ca. 40% machine efficiency (time actually spend in physics divided by scheduled time for physics operation).

- 3000 fb-1 for HL-LHC will require significantly better machine efficiency and average fill length above 6 hours (ca. 10 hours).

Consolidation of infrastructure!
But also new paradigm: remove as much as possible from the tunnel.
R2E SEU Failure Analysis - Actions

- **2008-2011**
  - Analyze and mitigate all safety relevant cases and limit global impact

- **2011-2012**
  - Focus on equipment with long downtimes; provide shielding

- **LS1 (2013/2014)**
  - Relocation of power converters

- **LS1 – LS2:**
  - Equipment Upgrades

- **LS3 -> HL-LHC**
  - Remove all sensitive equipment from underground installations
Availability and Machine Efficiency:
SC links ➔ removal of powering from tunnel

2×150 kA
Availability and Machine Efficiency:

- SC links
- Removal of powering from tunnel

\[ L = 20 \text{ m} \]
\[ (25 \times 2) \text{ 1 kA @ 25 K} \]

Feb 2014:
World record for HTS
Availability and Machine Efficiency:
SC links ➔ removal of powering from tunnel
Availability and Machine Efficiency:
SC links ➔ removal of powering from tunnel

1 pair 700 m 50 kA – LS2
4 pairs 300 m 150 kA (MS) – LS3
4 pairs 300 m 150 kA (IR) – LS3
tens of 6-18 kA CLs pairs in HTS
The critical zones around IP1 and IP5

1. New triplet Nb$_3$Sn required due to:
   - Radiation damage
   - Need for more aperture
   Changing the triplet region is not enough for reaching the HL-LHC goal!

2. We also need to modify a large part of the matching section e.g. Crab Cavities & D1, D2, Q4 & corrector

3. For collimation we also need to change the DS in the continuous cryostat: 11T Nb$_3$Sn dipole

- More than 1.2 km of LHC!!
- Plus technical infrastructure (e.g. Cryo and Powering)!!
Implementation plan:

- TDR: OCT 2015; TDR_v2: 2017
- Cryo, SC links, Collimators, Diagnostics, etc. starts in LS2 (2018)
- Proof of main hardware by 2016; Prototypes by 2017 (IT, CC)
- Start construction 2018 for IT, CC & other main hardware
- IT String test (integration) in 2019-20; Main Installation 2023-25
- Though but – based on LHC experience – feasible
Recent & Upcoming Project Milestones:

- May 2013: HL-LHC Collimation Review
- October 2013: RLIUP Workshop
- October 2013: 1st ECFA HL-LHC & Experiments Workshop
- May 2014: Crab Cavity Review
- November 2014: Super-conducting Cable review
- December 2014: MQXF Magnet review
- November 2014: 2nd ECFA HL-LHC & Experiments Workshop
- January 2015: Publication of the Preliminary Design Report
- March 2015: LIU and HL-LHC Cost & Schedule Review
- December 2015: End of EU funded HighLumi Design Study
Executive Summary

- The review committee is very impressed with the enormous amount of work that was presented.
- A very competent, engaged and effective management team is in place to manage both projects.
- The Project Management tools used at CERN are state of the art, well utilized and well understood by the management team.
- The presented project organizational structures are suitable to execute the projects. They matrix in-house as well as external resources very effectively into the organizations and they report directly to the Director of Accelerator and Technology.
- The QA and QC programs are well established, flexible and effective. They allow to manage foreign contributions, In-Kind participation and international collaborations effectively.
- The risk management program is somewhat new and should be fully integrated.
- The LIU and the HL-LHC project are well advanced in planning and execution for the stage they are in.

Congratulations!
Reserve Transparencies
Project approval milestones:

• June 2010: launch of High Luminosity LHC
• November 2010: HiLumi DS application to FP7
• November 2011: start FP7-HiLumi DS
• May 2013: approval of HL-LHC as 1st priority of EU-HEP strategy by CERN Council in Brussels
• May 2014: US P5 ranks HL-LHC as priority for DOE (Particle Physics Project Prioritization Panel)
• June 2014: CERN Council approves the financial plan of HL-LHC till 2025 (with an overall 10% budget cut)
LHC Upgrade Goals: Performance optimization

Luminosity recipe (round beams):

\[ L = \frac{n_b \cdot N_1 \cdot N_2 \cdot \gamma \cdot f_{rev}}{4\pi \cdot \beta^* \cdot \varepsilon_n} \cdot F(\phi, \beta^*, \varepsilon, \sigma_s) \]

1) maximize bunch intensities
2) minimize the beam emittance
3) minimize beam size (constant beam power);
4) maximize number of bunches (beam power);
5) compensate for ‘F’;
6) Improve machine ‘Efficiency’

Injector complex
Upgrade LIU
triplet aperture
25ns
Crab Cavities
minimize number of unscheduled beam aborts
FNAL: MBHSP01 – 1-in-1 Demonstrator (2 m)

40-strand cable fabricated using FNAL cabling machine

Coil fabrication

Collared coil assembly

Cold mass assembly

MBHSP02 passed 11 T field during training at 1.9 K with $I = 12080\,\text{A}$ on 5th March 2013!
# HL-LHC Baseline Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nominal LHC (design report)</th>
<th>HL-LHC 25ns (standard)</th>
<th>HL-LHC 25 ns (BCMS)</th>
<th>HL-LHC 50ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy in collision [TeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_b$</td>
<td>1.15E+11</td>
<td>2.2E+11</td>
<td>2.2E11</td>
<td>3.5E+11</td>
</tr>
<tr>
<td>$n_b$</td>
<td>2808</td>
<td>2748(^1)</td>
<td>2604</td>
<td>1404</td>
</tr>
<tr>
<td>Number of collisions at IP1 and IP5</td>
<td>2808</td>
<td>2736</td>
<td>2592</td>
<td>1404</td>
</tr>
<tr>
<td>$N_{tot}$</td>
<td>3.2E+14</td>
<td>6.0E+14</td>
<td>5.7E+14</td>
<td>4.9E+14</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.58</td>
<td>1.09</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>x-ing angle [$\mu$rad]</td>
<td>285</td>
<td>12.5</td>
<td>12.5</td>
<td>11.4</td>
</tr>
<tr>
<td>beam separation [$\sigma$]</td>
<td>9.4</td>
<td>12.5</td>
<td>12.5</td>
<td>11.4</td>
</tr>
<tr>
<td>$\beta^*$ [m]</td>
<td>0.55</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>$\epsilon_n$ [\mu m]</td>
<td>3.75</td>
<td>2.50</td>
<td>2.50</td>
<td>3</td>
</tr>
<tr>
<td>$\epsilon_L$ [eVs]</td>
<td>2.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>r.m.s. energy spread</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
<td>1.13E-04</td>
</tr>
<tr>
<td>r.m.s. bunch length [m]</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
<td>7.55E-02</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>80 -&gt; 106</td>
<td>18.5</td>
<td>18.5</td>
<td>17.2</td>
</tr>
<tr>
<td>IBS longitudinal [h]</td>
<td>61 -&gt; 60</td>
<td>20.4</td>
<td>20.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>0.65</td>
<td>3.14</td>
<td>3.14</td>
<td>2.87</td>
</tr>
<tr>
<td>Geometric loss factor R0 without crab-cavity</td>
<td>0.836</td>
<td>0.305</td>
<td>0.305</td>
<td>0.331</td>
</tr>
<tr>
<td><strong>Geometric loss factor R1 with crab-cavity</strong></td>
<td>(0.981)</td>
<td><strong>0.829</strong></td>
<td><strong>0.829</strong></td>
<td><strong>0.838</strong></td>
</tr>
<tr>
<td>peak-beam / IP without Crab Cavity</td>
<td>3.1E-03</td>
<td>3.3E-03</td>
<td>3.3E-03</td>
<td>4.7E-03</td>
</tr>
<tr>
<td>beam-beam / IP with Crab cavity</td>
<td>3.8E-03</td>
<td><strong>1.1E-02</strong></td>
<td><strong>1.1E-02</strong></td>
<td><strong>1.4E-02</strong></td>
</tr>
<tr>
<td>Peak Luminosity without crab-cavity [cm(^{-2})s(^{-1})]</td>
<td>1.00E+34</td>
<td>7.18E+34</td>
<td>6.80E+34</td>
<td>8.44E+34</td>
</tr>
<tr>
<td>Virtual Luminosity with crab-cavity: $L_{peak}*R1/R0$ [cm(^{-2})s(^{-1})]</td>
<td>(1.18E+34)</td>
<td><strong>19.54E+34</strong></td>
<td>18.52E+34</td>
<td>21.38E+34</td>
</tr>
<tr>
<td>Events / crossing without levelling w/o crab-cavity</td>
<td>27</td>
<td>198</td>
<td>198</td>
<td>454</td>
</tr>
<tr>
<td>Levelled Luminosity [cm(^{-2})s(^{-1})]</td>
<td>-</td>
<td><strong>5.00E+34</strong></td>
<td><strong>5.00E34</strong></td>
<td><strong>2.50E+34</strong></td>
</tr>
<tr>
<td>Events / crossing (with levelling and crab-cavities for HL-LHC)</td>
<td>27</td>
<td><strong>138</strong></td>
<td>146</td>
<td>135</td>
</tr>
<tr>
<td>Peak line density of pile up event [evt/mm] (max over stable beam)</td>
<td>0.21</td>
<td><strong>1.25</strong></td>
<td>1.31</td>
<td>1.20</td>
</tr>
<tr>
<td>Levelling time [h] (assuming no emittance growth)</td>
<td>-</td>
<td><strong>8.3</strong></td>
<td>7.6</td>
<td>18.0</td>
</tr>
</tbody>
</table>

\(^1\)ATS required

IPAC 2015, Mai 2015, Richmond, USA
LHC Upgrade Goals: Performance optimization

• Levelling:

Luminosity limitation(s):
• Even Pileup in detectors
• Debris leaving the experiments and impacting in the machine (magnet quench protection)
• Triplet Heat Load
The **Achromatic Telescopic Squeezing (ATS) scheme**

Small $\beta^*$ is limited by aperture but not only: **optics matching & flexibility** (round and flat optics), chromatic effects (not only $Q'$), spurious dispersion from X-angle, ..

A novel optics scheme was developed to reach un-precedent $\beta^*$ w/o chromatic limit based on a kind of generalized squeeze involving 50% of the ring

---

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS

“pre-squeezed” optics (left) and “telescopic” collision optics (right)

---

(S. Fartoukh)
The **Achromatic Telescopic Squeezing (ATS) scheme**

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A novel optics scheme was developed to reach un-precedent $\beta^*$ w/o chromatic limit based on a kind of generalized squeeze involving 50% of the ring

$\beta^* = 40$ cm

$\beta^* = 10$ cm

→ Proof of principle demonstrated in the LHC down to a $\beta^*$ of 10-15 cm at IP1 and IP5

Beam sizes [mm] @ 7 TeV from IR8 to IR2 for typical ATS “pre-squeezed” optics (left) and “telescopic” collision optics (right)

The new IR is sort of 8 km long!
LHC low-β quads: steps in magnet technology from LHC toward HL-LHC

LHC (USA & JP, 5-6 m)
Ø70 mm, B_{peak} \sim 8 T
1992-2005

LARP TQS & LQ (4m)
Ø90 mm, B_{peak} \sim 11 T
2004-2010

New structure based on bladders and keys (LBNL, LARP)

LARP HQ
Ø120 mm, B_{peak} \sim 12 T
2008-2014

LARP & CERN MQXF
Ø150 mm, B_{peak} \sim 12.1 T
2013-2020
The HL-LHC Nb-Ti magnet zoo...

D1 (KEK)

Nested Orbit corrector (CIEMAT)

HO correctors: superferric (INFN)

D2 (INFN)

Q4 (CEA)

D2 corr
SPS beam test: a critical step for CC (profiting of the EYETS 2016-2017)

SPS test is critical: at least one cryomodule before LS2, possibly two, of different cavity type.

A test in LHC P4 is kept as a possibility but it is not in the baseline.

∅ = 90 mm. 2 K
11.6 MV required voltage;
baseline is 4 cavities/beam-side, ⇒ 2.9MV/cavity
Low impedance collimators (LS2 & LS3)

New material: MoGr

Reduce impedance by > 2)  
S. Redaelli et al.
Efficiency for $\int L \, dt$

- All our assumptions are based on forecast for the operation cycle:

$$\eta \geq 50\%$$

High reliability and availability are key goals

\[ L_{\text{virt}} = 20 \cdot 10^{34}, \quad N_{\text{ppb}} = 2.2 \cdot 10^{11} \]
Controlling halo diffusion rate:
hollow e-lens (synergy with LRBBCW)

Promises of hollow e-lens:
1. Control the halo dynamics without affecting the beam core;
2. Control the time-profile of beam losses (avoid loss spikes);
3. Control the steady halo population (crucial in case of CC fast failures).
Remarks:
- very convincing experimental experience in other machines!
- full potential can be exploited if appropriate halo monitoring is available.
In-kind contribution and Collaboration for HW design and prototypes

Q1-Q3 : R&D, Design, Prototypes and in-kind USA
D1 : R&D, Design, Prototypes and in-kind JP
MCBX : Design and Prototype ES
HO Correctors: Design and Prototypes IT
Q4 : Design and Prototype FR
High Luminosity LHC Participants
High Luminosity LHC Participants
HL-LHC Challenges: Collimation Efficiency

<table>
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<tr>
<th>Primary</th>
<th>Secondary</th>
<th>Absorbers</th>
<th>Dump Kicker</th>
<th>Dump Protection</th>
<th>Tertiary</th>
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<td>7σ</td>
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Collimator type | $N_i$ | Collimator type | $N_i$
---|---|---|---
TCP IR3 | 8σ | TCDQ IR6 | 8σ |
TCSG IR3 | 9.3σ | TCSG IR6 | 7σ |
TCLA IR3 | 10σ | TCLI IR2/IR8 | 6.8σ |
TCP IR7 | 5.7σ | TCT IR2/IR8 | 25σ |
TCSG IR7 | 6.7σ | TCT IR1/IR5 | 15σ |
TCLA IR7 | 10σ | TCL IR1 | 20σ |

2012
‘Tight’ = Iberian Peninsula 2.2mm

2011
‘Interm.’ Norway = 3.1mm

1σ (450GeV) ≈ 1mm
1σ (4TeV) ≈ 0.35mm
1σ (6.5TeV) ≈ 0.25mm
HL-LHC: Maintain and increase physics reach!!!

Necessity of a jump in luminosity (useful luminosity ⇒ data quality)
3 Crab Cavity prototypes:

- RF-Dipole Nb prototype [ODU-SLAC]
- 4-rod in SM18 for RF measurements [Lancaster UK]
- 4-rod prepared for rinsing @ CERN
- DQWR prototype (17-Jan-2013) [BNL]

Concept of RF Power system
Integrated Luminosity 2010-2012

- 2010: 0.04 fb⁻¹
  - 7 TeV CoM
  - Commissioning
- 2011: 6.1 fb⁻¹
  - 7 TeV CoM
  - Exploring the limits
- 2012: 23.3 fb⁻¹
  - 8 TeV CoM
  - Production

⇒ x 60 in 2 years!
LHC: big (27km), cold (1.8K), high energy (7 TeV on 7 TeV)

- Beam dumps
- Collimation
- Injection B2
- 2-in-1 magnet design ➔ p-p, Pb-Pb & p-Pb collisions

- Injection B1
- Collimation
- CMS
- RF
- LHCb
- ATLAS
- CERN Meyrin
- SPS, 7 km
- CERN Tandem
- ALICE
- LHC – 27 km

1720 Power converters
> 9000 magnetic elements
7568 Quench detection systems
1088 Beam position monitors
4000 Beam loss monitors

150 tonnes Helium, ~90 tonnes at 1.9 K
140 MJ stored beam energy in 2012
370 MJ design and > 500 MJ for HL-LHC!
450 MJ magnetic energy per sector at 4 TeV ➔ ≈ 10 GJ total @ 7 TeV
## Intervention rate & time: QPS boxes

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Consolidation of infrastructure!
But also new paradigm: remove as much as possible from the tunnel.